Vehicle Maintenance

Information on the maintenance performed on CleanFleet vehicles is presented in two parts. The approach used to collect maintenance data is described. Then maintenance activities on fuel-related systems and a statistical summary of maintenance activities are provided.

Approach

Information on maintenance activities that appeared to be fuel related was obtained by monitoring FedEx repair order data and through discussions with FedEx mechanics at each of the five participating demonstration sites and representatives from vehicle manufacturers, local vehicle dealers, and third-party vendors (i.e., Southern California Edison, IMPCO, Suburban Propane). Following the narrative description of maintenance activities are statistical summaries of the maintenance data reported by FedEx mechanics, vehicle manufacturers, dealers, and vendors. The procedures used to collect, process, and analyze the CleanFleet maintenance data are discussed below.

Data Collection. Vehicle maintenance data were obtained from

- FedEx vehicle repair orders
- Warranty and maintenance information obtained from vehicle manufacturers, local dealers, and third-party vendors
- Daily Vehicle Use and Repair Reports (VURRs).

FedEx maintains an information system on all repairs to its fleet vehicles. This system is called the **V**ehicle **a**nd **G**round Support Equipment **I**nformation **S**ystem (VAGIS). Maintenance data on all demonstration vehicles were periodically transferred from VAGIS to Battelle in electronic form and placed into the CleanFleet database. The data include date of repair, repair order number, mechanic employee number, party responsible for the repair (vendor or FedEx), reason for the repair (e.g., scheduled, breakdown, driver report), type of repair, labor performed, parts replaced, and cost of labor and parts. All labor and parts replaced are reported using American Trucking Associations (ATA) codes.

In addition to the information supplied by VAGIS, Battelle also obtained data from local dealers and other organizations who performed certain warranty repairs. Information on manufacturer warranty repairs were received directly from the manufacturers. Two of the three vehicle manufacturers (Chevrolet and Dodge) provided costs on all fuel-related warranty repairs. Maintenance data on the electric vehicles were obtained from Southern California Edison. The data received from FedEx, vehicle manufacturers, local dealers, and vendors were reviewed by Battelle for accuracy and completeness. After reconciling any differences, the data were combined into a single maintenance database containing approximately 6,500 repair orders.

Each time a FedEx employee drove a fleet vehicle, he or she was required to record its use and report any problems on a VURR. Mechanics reviewed the VURRs daily and recorded any maintenance performed.

Battelle received copies of all VURRs to monitor this communication between drivers and mechanics. The data maintained in the CleanFleet database included date of use, vehicle identification number, and a description of problems reported. The data were primarily used to monitor oil consumption as it was reported by couriers during their early morning vehicle check.

Data Processing. Data from FedEx's VAGIS were transmitted to Battelle on a bi-weekly basis during the course of the demonstration. Battelle developed software applications that reduced and stored the VAGIS data in appropriate files for data analysis. A second set of application programs was run against the data to ensure their validity and integrity. Questionable data were flagged and reported, and problems were resolved before the data were included in any reports or statistical analyses.

Repair and maintenance data from vehicle manufacturers, dealers, and vendors were received on hard copy forms and keyed into separate data sets. The data from all sources were merged with the VAGIS data and cross-checked to ensure that only one occurrence of a vehicle repair was retained in the final CleanFleet database. After these data processing steps were completed, several adjustments were made to allocate total costs between labor and parts and to account for certain types of missing data. These adjustments are discussed below.

Some repair orders (ROs) were excluded from the final analysis of the data. These ROs involved issues that Battelle determined were external to the fuel/vehicle system under study. For example, repairs associated with vehicle accidents, installation of additional CNG fuel tanks, vehicle fires, and the introduction of contaminated fuel into the vehicles were eliminated from the database before final analysis. These issues generate repair requirements and costs, but the repairs are not the type that are of direct interest to this study.

Data Analysis and Reporting. Maintenance costs and the frequency of maintenance activities are detailed in a series of six data reports contained in Appendix A. The key results are presented in the "Results" section. These include the number of repair orders per 100 service days (a measure of the overall frequency of repair actions), total maintenance costs, and vehicle availability and utilization.

The six data reports in Appendix A contain detailed information about the maintenance performed for each fleet (unique combinations of fuel type, manufacturer, and demonstration site). Each report aggregates the data at two levels: (1) all maintenance activities performed and (2) maintenance on selected vehicle systems that are more likely to involve problems with the fuels or the fuel delivery technologies. The selected vehicle systems include instruments (ATA system code 003), electrical group (030 - 035), and engine/fuel systems (040 - 048).

The first data report summarizes the preventive maintenance (PM) activities in terms of number of PMs performed, labor hours, labor costs, and parts costs. The next five reports summarize the non-preventive maintenance activities in terms of number of ROs, labor hours, labor costs, parts costs, and total costs. The total number of ROs per fleet is presented along with normalized values based on the number of vehicles, total miles driven, and number of days in service. Similarly, the labor hour and cost parameters are normalized to the number of ROs, miles driven, and number of days in service.

Vehicle availability is generally defined as the percent of normal operation time that a vehicle is available for use, whether or not the vehicle is used. For FedEx, normal operation is generally between the hours of 7:00 AM and 8:00 PM, Monday through Saturday. There are some site-to-site differences in operations times.

Vehicle availability (A) was calculated as

$$A = (T\text{-}D)/T,$$

where, for each vehicle, T is the total hours of normal operation between the first and last day the vehicle participated in CleanFleet, excluding time required for CleanFleet emissions testing, and D is the total hours of downtime due to maintenance activities. Periods of time in which a vehicle was available but not used by FedEx are included in T, but not in D. On the other hand, the time a vehicle was waiting to be repaired is included in D.

Downtime (D) was usually calculated by FedEx as part of the normal data processing within VAGIS. When FedEx mechanics prepare ROs, they report the date and time of day when the vehicle is taken out of service and the date and time when the vehicle is returned to service. The VAGIS information management system calculates “downtime” as the amount of operation time that the vehicle is out of service. Note that if the vehicle is taken out of service after 8:00 PM and returned to service before 7:00 AM the next day, the downtime is zero.

However, the VAGIS database did not always contain complete information on out-of-service time for vehicles repaired at vendors. When ROs obtained from VAGIS, vendors, and the OEMs contained duplicate or complementary information about a single maintenance incident, the information was combined by Battelle into a single repair order. This often involved modifying the return-to-service date on the combined repair order. Occasionally, the repairs performed by vendors were not entered into VAGIS by FedEx mechanics. The only information available was the repair order provided by the vendor. Many times these repair orders did not contain complete information about downtime. In particular, the times at which the vehicle went out of service or returned to service were often not available. If the out-of-service date and the return-to-service date were reported, downtime was calculated by assuming that the vehicle was out of service for half of the first day and all the succeeding days. For example, the downtime for a vehicle serviced by a vendor within one day was estimated to be approximately 6.5 hours.

In some cases, especially those involving dealer repairs, the return-to-service date was also missing. A random sample of these repairs was investigated individually, using the vehicle activity data to determine the best estimate of downtime.

Vehicle availability for a fleet was calculated after summing the values of T and D, respectively, for each vehicle. Availability was calculated separately on the fleets of unleaded vans from each manufacturer at each demonstration location. That is, the average availability is calculated for each combination of fuel type, vehicle manufacturer, and location.

Vehicle utilization is defined as the percent of scheduled service days that a vehicle was actually used in delivery service. Vehicle activity data, reported by drivers, were used to calculate utilization. Utilization was calculated by first determining for each van (1) the number of weekdays (Monday through Friday) on which the van was driven (utilized) and (2) the total number of weekdays between the first and last day the van was scheduled to be used. The sum of the days utilized was then divided by the sum of the days scheduled (after subtracting the number of days vehicles were at the California Air Resources Board for emissions testing) to determine the utilization for each fleet. Saturdays and Sundays were excluded from the calculation because FedEx stations are closed on Sunday and because there are differences in Saturday delivery requirements among the five demonstration sites.

Data Adjustments. To present a more complete and accurate picture of the maintenance performed on CleanFleet vehicles, it was necessary to make certain adjustments to the data reported by the various organizations. The adjustments account for the ways in which certain vendors report cost details and FedEx's procedures for reporting warranty costs.

A computer check of the relationship between labor hours and labor costs revealed that, for many of the non-preventive maintenance repairs from vendors, values were missing or inconsistent. Three types of data adjustments had to be made.

(1) The first problem affected labor records from non-preventive maintenance repair orders in which either labor hours or costs were not adequately reported. Adjustments made on individual labor records are discussed below.

(a) For some labor items, the number of labor hours appeared realistic; but the total cost was shown as $0.01, zero, or missing. In this case, it was assumed that the repair work was being performed under warranty and that the vendor or FedEx mechanic correctly reported the labor hours. The labor costs were re-calculated as the number of labor hours times an average rate of $20 per hour.

(b) For some labor items, the labor cost was a significant positive number but was not consistent with the number of labor hours reported. For example, a vendor might report several hundred dollars of labor on an item but not report the actual number of hours worked. When entering the information in VAGIS, the FedEx mechanic simply reported one hour of labor. For these types of records, the cost was assumed to be correct; and the labor hours were calculated as the total cost divided by the average labor rate of $20 per hour. This adjustment was made whenever the calculated rate, based on the reported cost and labor hours, fell outside the range of $10 to 35 per hour.

It should be noted that the average rate of $20 per hour used in (a) and (b) above was approximately the average hourly rate when calculated across all labor records in the detailed record database that did not have either of those types of data problems.

(2) The second type of data adjustment was needed because some vendors reported the total cost for a repair, but did not allocate the costs between labor and parts. The total costs were divided equally between labor and parts. Next, the costs allocated to labor were divided by the average labor rate of $20 per hour to calculate estimated labor hours.

(3) The third type of data adjustment was required in cases where vendors described the work that was accomplished but did not provide any cost information. In those cases, Battelle staff searched the database for other similar repairs to provide an estimate of the labor hours and parts cost involved. Labor costs were calculated using the average rate of $20 per hour.

Results

Results are provided in two parts. First, maintenance on fuel-related systems is described. Then, a statistical summary of maintenance actions is presented.

Description of Fuel-Related Maintenance. Fuel-related maintenance activities are summarized below.

Propane Gas. Twenty CleanFleet vehicles were fueled with propane gas. In May 1992, 13 Ford vans were modified to run on propane gas. Modifications of the seven Chevrolet vans were not completed until October 1992. These vans were not OEM production propane vans, and their maintenance histories should be viewed in that light.

All the CleanFleet propane gas vans had problems with the fuel quantity gauge mounted on the instrument panel. The reading on this gauge depended on a tank-mounted float sensor in the horizontally mounted cylindrical propane tank, which did not have internal baffling to prevent fuel sloshing or errors caused by unlevel ground. However, the drivers did not rely completely on the dash-mounted gauge. They checked a tank-mounted gauge at the start of the day when the vehicle was stopped on level ground. Further, the drivers knew how far they could drive on a tank full of liquefied propane gas (LPG).

Chevrolet. The Chevrolet vans were modified to operate on propane gas by an outside contractor. Upon inspection of these installations, Battelle, FedEx, and IMPCO decided that some of the equipment needed to be removed and installed differently. IMPCO personnel reinstalled the equipment. After the modifications, the propane receptor fittings on the Chevrolet vans had to be reconfigured from a straight head fitting to an angled fitting so that the propane dispensing nozzle at the demonstration site could attach to the vans.

Two Chevrolet propane gas vans were out of service in November 1992 because of rough running and stalling. On one of these vans the idle air control (IAC) grommet blocked the air bypass passage; replacing this grommet solved the problem. The other van had low secondary fuel pressure. Replacing the fuel pressure regulator solved this problem.

Two Chevrolet vans were repaired for surging problems under cold operating conditions in December 1992. This problem was traced to the mixture control valves, which were replaced.

In February 1993, a contaminated oxygen sensor failed in one Chevrolet van. This sensor was replaced; however, the source of the contamination was never positively identified.

The gas mass sensor/mixture control valves in all of the Chevrolet propane gas vehicles were replaced in March 1993. Inspection of the gas mass sensors showed that they all had a manufacturing defect and were not internally grounded as they should have been. They were replaced with gas mass sensors that were properly grounded.

The originally installed control fuses were mounted in an in-line fuse holder near the battery in the Chevrolet vans. After some time in operation, vapors from the battery corroded the fuse and interfered with reliable vehicle operation. These fuses were relocated in a weather-resistant fuse holder near the center of the firewall of the vehicle, which resolved the problem.

In April 1993, a Chevrolet van provided to the California Air Resources Board (ARB) for emissions testing refused to idle correctly. Testing of this vehicle was terminated, and IMPCO was notified. Upon inspection, it was discovered that a vacuum port on the throttle body had not been properly blocked. Blocking this port resolved the problem.

In May 1993, new fuel lockoff valves (with a higher temperature tolerance than the original lockoffs) were installed in all Chevrolet vans. The lockoff is an electrical solenoid operated valve that prevents fuel flow when the vehicle is not running. The original valves installed proved to be temperature sensitive. Once the vehicle reached operating temperature during hot weather and was shut down, the heat-soaked lockoff valves made it impossible to restart the vehicles when the engines were hot. New lockoff valves were installed as a precautionary measure because the Ford vans with the same type of valves had experienced trouble in the summer of 1992. The Chevrolet vans were placed in service after the hot weather in 1992.

In May 1993, it was discovered that the idle speed on the Chevrolet propane vans had dropped. This change was attributed to operating the vehicles. The idle speed of all Chevrolet propane vans was restored to the original setting.

Error code and driveability problems with one Chevrolet van were corrected in May 1993. This van and two others were drawing fuel from the vapor in the fuel tank rather than from the liquid, and their fuel supply lines had to be switched to the correct locations. This change resolved the driveability problems with these vehicles. Also, all propane gas powered vans were checked for proper hookup.

Some components in the circuits of the gas mass flow sensors on the Chevrolet vans could not tolerate the heat during the summer of 1993. These units were redesigned, and new units that were more tolerant of summer temperatures were installed. This change solved the problems.

Primary seats in the regulators delaminated, causing a loss of pressure and preventing proper metering of the fuel. Rubber disks attached to a metal part were detaching from the metal. IMPCO worked with the manufacturer to develop an improved attachment process, and all the seats in the propane gas and IMPCO-equipped natural gas vans were replaced.

A continuing problem was experienced with dirt in the throttle bodies of the Chevrolet propane gas vans using AFE. These vans were operated in a desert-like area, which may have played a role in the problem. However, gasoline-fueled vehicles operated in these conditions do not experience the same degree of problem. The gasoline tends to wash the dirt out of the throttle body, while propane does not. Cleaning the throttle bodies of propane vehicles should be done on a regular basis, i.e., every 10,000 to 12,000 miles.

Because the original IAC grommets between the idle air control valve and the throttle body were not tolerant of the propane fuel, they started to leak after a period of operation. The original grommets were replaced with grommets of a more compatible material.

Deterioration of the gasket between the air cleaner and throttle body appeared to be a durability rather than a fuel compatibility issue. The original gaskets were replaced with more durable parts.

By September 1993, IMPCO had completed a series of maintenance actions on all the Chevrolet propane gas vans because they had been running poorly. In addition, IMPCO used this general maintenance of the vans to introduce technology updates to their equipment. The actions taken were to

- Replace the diaphragm in the pressure regulator with a fluorosilicone diaphragm
- Replace the S4-7 seat in the regulator
- Adjust the idle speed
- Clean the throttle body
- Replace the oxygen sensor
- Update the erasable, programmable read-only memory (EPROM).

In September 1993, a bad ground wire on one Chevrolet electronic control unit board was repaired.

In November 1993, a Chevrolet propane gas vehicle would not start. IMPCO asked FedEx to clear the “block learn,” and use the van for several days before bringing it into IMPCO. IMPCO found a problem on the ECU board and also determined that the block learn strategy had a problem. Repairs were made and the van operated without problems. A second Chevrolet van started displaying the same symptoms and would not function even after the block learn was cleared. Eventually, this was resolved.

A defective gas mass sensor in another Chevrolet propane gas van was replaced in November 1993.

The block learn fuse of a different Chevrolet propane gas van was pulled daily to keep the van in operation in January 1994. This was another AFE software problem that was subsequently resolved by IMPCO.

In January 1994, a bent primary pressure regulator diaphragm with a small accumulation of oil in the regulator was found in one of the Chevrolet propane gas vans. This van was in for repair for 35 days.

In February 1994, a Chevrolet propane gas van was removed from service for poor performance. A check of the fuel system showed that no liquid was being drawn from the tank because the lines were incorrectly connected. This problem had been noted in some vans in May of 1993 and all the vans were checked at that time to make sure that the fuel system connections were correct. Apparently the inspection was inadequate.

All Chevrolet propane gas vans were serviced between July and September 1994 to tune up the vehicles and to install updated fuel lockoff valves, an updated EPROM, and a more durable tank-mounted fuel gauge.

Ford. In August 1992, faulty fuel lockoffs were replaced in the Ford vehicles. The lockoff is an electrical solenoid operated valve that prevents fuel flow when the vehicle is not running. The original valves proved to be temperature sensitive. Once the vehicles reached operating temperature during hot weather and were shut down, the heat-soaked lockoff valves made it impossible to restart the vehicles when the engines were hot. These valves were replaced by less temperature-sensitive ones, which resolved the problem.

A problem with the "check engine" light in some of the Ford propane gas vehicles was discovered in September 1992. The van's OEM computer was receiving false signals indicating that a problem existed with the emission control system. The OEM microprocessors were still programmed as if the vehicles were operating on gasoline. To correct the fault, IMPCO manufactured a device (an ADP diagnostic box) to intercept the faulty signal and pass an acceptable signal on to the OEM computer. This device was installed in all Ford vans by July 1993.

In February 1993, the primary diaphragm in the fuel regulator was replaced in a Ford van. In March 1993, the diaphragm was replaced in two more Ford vans. The diaphragm was replaced in a fourth Ford van in May 1993. The diaphragms of all the Ford vans were replaced with fluorosilicone diaphragms in June 1993. The problem was traced to a material incompatibility between the original diaphragm material and the propane fuel. This change resolved the problem.

Delaminated primary seats in the regulators caused a loss of pressure in the regulator and prevented proper metering of the fuel. These seats consist of rubber disks attached to a metal part, from which the rubber was detaching. IMPCO worked with the manufacturer to develop an improved attachment process, and all of the seats in the propane and IMPCO-equipped natural gas vans were replaced.

In June 1993 an ADP processor on one of the Ford vans had to be replaced. It was commanding a very rich mixture, preventing the van from passing the emissions test. After replacement of the processor, the carbon monoxide level dropped from over 5 percent to less than 0.05 percent.

The tachometer signal for the ADP was too weak for reliable vehicle operation. In July 1993, the location from which that signal was taken was changed to provide the ADP with a stronger signal, which resolved the problem.

Temperature-sensitive fuel-control valves on the Ford vans were replaced in July 1993 with less temperature-sensitive and more durable units.

The "check engine" light illuminated on a regular basis in late 1993 through February 1994 on several Ford propane gas vans. This problem first arose in September 1992. IMPCO developed a diagnostic box to intercept the faulty signal and pass an acceptable signal on to the OEM computer. This device was installed in all Ford vans by July 1993. The strategy used by this box proved to be incorrect; it seemed to solve the problem for a few months, but the problem resurfaced. New diagnostic boxes, using an updated strategy, were installed during July and August 1994.

In August and September 1994, the hoses used to carry coolant from the cooling system to the regulator to heat the LPG started to deteriorate. These hoses were replaced with better quality hoses. Also, more durable tank-mounted fuel gauges were installed in this same period.

<u>Compressed Natural Gas</u>. There were 21 CNG fueled vehicles in the CleanFleet demonstration. By October 1992, three Ford vans and seven Chevrolet vans were modified to run on CNG. Modifications on two more Ford vans were completed in November 1992. The seven Dodge vans were supplied by Chrysler as production CNG vehicles, generally available to the public as of June 1992.

The CNG vans used fuel quantity gauges that measure the amount of natural gas remaining in the tanks. A pressure transducer measures the pressure in the tanks. This reading is passed to a module that sends a signal to the dash-mounted fuel gauge indicating the amount of fuel remaining. This system did not prove sufficiently reliable for FedEx operations. Several changes were made, including replacing the control modules and transducers with units that are pressure and temperature compensated. However, the fuel gauges still were not reliable.

Chevrolet. Early in the demonstration, two Chevrolet CNG vans were out for a day to fix cold surging problems. Throughout the next several months, problems continued with this fleet of CNG vans. The problem was traced to the block learn mode in the computer. These vehicles were programmed with a default set of engine parameters (e.g., ignition timing), which were changed progressively according to the driving cycle of the vehicle. The changes are supposed to allow better operation of the vehicle. In this case, however, the software degraded vehicle operation the farther the vehicles were driven. Eventually, the vehicles became undriveable and even unstartable. A number of interim fixes were tried to address various problems with the vehicles until the basic problem was identified and correct software was prepared and installed in September 1993.

Significant amounts of compressor oil (generally varying between 30 and 70 milliliters) were found in the Chevrolet regulators. The oil displaced a like volume of fuel in the regulator and caused problems, especially when the vans were driven under load (e.g., hard acceleration or uphill).

The gas mass flow sensor assemblies were replaced on the Chevrolet vans in February 1993 to correct problems with cold starting and poor performance. As in the propane gas vehicles, these gas mass flow sensor assemblies had an internal grounding manufacturing defect. These sensors were replaced with properly manufactured units.

Also, as in the propane gas vehicles, the fuse from the electronic control module was moved and a new sealed in-line fuse holder was installed to prevent fuse corrosion. The idle air control gaskets were also replaced.

Three Chevrolet vans continued to stall during May and June 1993. The oil filter tube was inadvertently rubbing against, and grounding, the body of the gas mass flow sensor. When the flow sensor was remounted or relocated on all the vans, they ran without problems.

As a precaution, the gas mass flow sensors and pressure regulators were replaced on all the Chevrolet natural gas vans. Also, all vans received an EPROM update. This was done because the corresponding propane gas vehicles using these components were having problems.

In February 1994, a van broke down on its delivery route. The engine would crank but not start and there was a strong odor of natural gas under the hood. Another van was removed from service for a surging problem at cruise speed. This van had a defective gas mass flow sensor.

Another van was removed from service in March for poor performance and delivered to IMPCO. The gas mass flow sensor was replaced, and the regulator was remounted so that it would have less chance of retaining compressor oil entering with the CNG during fueling. IMPCO instituted a program to remount all the regulators so they would be less likely to trap oil.

A Chevrolet CNG van was removed from service by IMPCO because the clearance between the tank and frame appeared inadequate. The tank was removed and a new tank installed with increased clearance. Subsequently, all tanks were inspected, with the result that two were removed and replaced due to damage.

In June 1994, two Chevrolet CNG vans were sent to IMPCO with stalling problems. IMPCO serviced the throttle body and adjusted the minimum idle speed on one van, while replacing the gas mass flow sensor, servicing the throttle body, and completely tuning up the other.

In August 1994, a van overheated while returning to the station. The driver was instructed by her manager to try driving it the rest of the way back. Subsequently, a radiator hose ruptured, wetting the ignition system and causing a short. The vehicle was towed in, and inspection showed significant engine damage. A new CNG engine was installed.

Dodge. A Dodge van was out of service for a pressure regulator problem in October 1992. The regulator was replaced, but the reason for its failure is not known.

One Dodge van was at a dealership throughout May 1993. The van was returned to service in June 1993 after several repairs to the fuel system.

Leaks were found in the fuel lines in two Dodge vans in May 1993. The leaks were stopped by properly torquing the fittings.

In June 1993, a revised CNG-calibrated engine computer and a new regulator were installed in a Dodge van that would not idle. These changes resolved this problem.

Pressure gauges were installed at the fuel tanks in six Dodge vans in November 1993. The instrument panel fuel gauges were not accurate and could not be relied upon to correctly reflect the amount of fuel remaining in the tank. The Chevrolet vans already had such fuel tank pressure gauges, and the other Dodge van was out of the station when the gauges were installed. (The pressure gauge was installed on this van in January 1994.)

Obtaining prompt service from the local Dodge dealer was a problem. A Dodge CNG van delivered for service to the dealer was sometimes not looked at for a week or longer. Therefore, these vans probably were less available for service than if they had been given prompt support from the dealer.

One van spent 16 days at the dealer. During this time a regulator and ECU were replaced, but the van continued to run poorly. Finally, replacing two injectors allowed the van to be returned to service. However, this problem resurfaced early in February, necessitating further work.

An idle problem sent a CNG Dodge van to the dealer for 14 days in February. The dealer replaced a pressure regulator and a motor.

A van was returned to the dealer when it began running rough. It appeared that the catalytic convertor was coming apart.

In February, a CNG Dodge van would not accept fuel because of a stuck check valve. Another van was out of service for four days due to a faulty idle speed motor. Upon its return to service, it ran a half day and had to be towed to the dealer.

A CNG Dodge van was out of service for 8 days due to a stalling problem in traffic. The dealer cleaned the throttle body and cleared the computer memory and returned the van to service.

Ford. In November 1992, one Ford CNG van experienced rough running and misfiring, with the "check engine" lighted. Even after a processor was replaced in December 1992, this vehicle ran roughly and remained out of service throughout the month. In January 1993, compressor oil was found in the pressure regulator of one of the vans, which was the cause of the rough running and misfiring. Problems with fuel injectors were also traced to compressor oil. The injector manufacturer, Bosch, indicated that these injectors could be cleaned and returned to service; however, some injectors were replaced before this was known.

After a few months of service, Ford replaced all regulators on all natural gas vehicles. Some regulators had been manufactured incorrectly without internal sintered metal filters. However, no attempt was made to determine which regulators lacked these filters; all regulators were replaced.

In April 1993, one Ford van developed a leak in a fuel tank solenoid valve. This leak occurred inside the FedEx building, which had been equipped with flammable gas detectors. The alarm did not sound, but the building was evacuated. After review of the sensor records, it was discovered that, at the time the building was evacuated, the level of gas in the building was less than 10 percent of the lower explosion limit. Because the alarm threshold is set at 20 percent of the lower explosive limit, the alarm would not have been expected to sound in this instance. The van responsible was identified and pushed outside, allowing the building to be reoccupied. The solenoid valve was replaced and sent to the manufacturer, where internal corrosion was discovered. This valve was redesigned and new valves stocked to replace future failures.

Three Ford vans would not take a full fueling in June 1993, and another Ford van exhibited the problem in August 1993. A manual lockdown on the fuel tank solenoid may have been the cause. When the lockdown is screwed in, a nylon insert broke loose and blocked the passage. This went undetected when the lockdown was unscrewed. The short-term fix was to remove and replace the existing manual lockdown if it was suspected of causing a problem.

Fuel tank pressure gauges were installed in six Ford vans in November 1993. The instrument panel fuel gauges were inaccurate and did not reliably reflect the amount of fuel remaining in the tank. The Chevrolet vans already had such fuel tank pressure gauges, and the seventh Ford was out of the station when the gauges were installed.

In February, a minor leak occurred in one of the CNG fuel lines, necessitating replacement of the line.

A CNG Ford van was sent to the dealer in early March for engine misfiring. The dealer discovered worn plugs and replaced them with platinum-tipped spark plugs. Ford indicated that the CNG fuel stresses the ignition system much more than gasoline. This condition may cause misfiring or failure to properly ignite the mixture. The condition may go unnoticed in normal operation. Results of emissions testing showed less than a 5 percent decrease in nonmethane hydrocarbons using the platinum spark plugs.

M-85. By April 1992, modification of 13 of the Ford M-85 vans was complete. By October 1992, all M-85 vehicles were in service, with the exception of two Ford vans, one of which was out of service for a fuel leak and the other for fuel pump noise. The fuel leak was traced to an improperly tightened fuel rail, and the noisy fuel pump was replaced even though it seemed to be operating properly.

Two vehicles were pulled from service in November 1992 when they lost power as a result of fuel contamination from a dispenser hose that was incompatible with M-85. The fuel tanks of all M-85 vehicles were cleaned and the fuel filters replaced. After this, the dispenser hose was replaced with one compatible with M-85.

In February 1993, two Ford vans were out of service because of a broken wire in the fuel control modules. This proved to be a manufacturing defect and was resolved by replacing the modules.

In March 1993, five other Ford M-85 vehicles began to have problems with the fuel control modules (FCM), and the modules were replaced. In April 1993, a sixth Ford had problems with the FCM, which was also replaced. In May and June 1993, the fuel control modules were replaced in all the Ford M-85 vans. Inspection revealed that the pickup tubes on the FCM were too long and were rubbing the inside of the tank, which removed the plating. The plating passed through the fuel system, damaging the fuel pump. Fuel control modules with shorter pickup tubes were installed, and the fuel lines and filters were replaced.

Three of the Ford vans had difficulty accepting fuel at full flow rates. Ford suspects that this problem involves the anti-siphon device in the fuel tank filler tube.

Two M-85 vans experienced engine compartment fires in late 1993. These problems were traced to the cold start injector housings. Cold start systems are not required in the Los Angeles climate; therefore, all cold start systems were subsequently removed from these developmental M-85 vehicles.

Injectors and spark plugs were replaced in one van because of a slight misfiring problem.

In January 1994, a defective fuel pump was replaced in one van. This failure did not appear to be related to the use of M-85 fuel or to debris in the fuel system.

Injectors and spark plugs were replaced in an M-85 van in February because of misfiring. A third van experienced the same problem in March. A faulty injector caused this problem; all injectors were replaced.

A defective fuel pump was replaced in an M-85 Ford van in April 1994. No fuel-related problems were evident.

In the fall of 1994, it was decided that only the two M-85 vans scheduled for engine teardown would continue to operate on M-85. The remainder would operate on gasoline. Subsequently, several of the gasoline-fueled vans ran out of fuel on their routes. The M-85 fuel had caused a build-up on the card sender in the fuel tank. The card sender sent a full (or nearly full) signal to the dash-mounted fuel gauge regardless of the amount of fuel in the tank.

Electric. The electric vans with the PbA batteries required maintenance on the battery packs and traction motors, which were replaced on both vehicles. Some of the work on the PbA vans was done to increase their driving range, not because the batteries required maintenance. In contrast, the Ni-Cd van did not require significant maintenance during the time it was demonstrated. Because of the low range of one of the electric vans, the battery pack was replaced by SCE in early June 1992. After a 40.7-mile controlled drive, the battery pack showed a 1/8 charge remaining. (The range potential shown by this SCE driving cycle probably cannot be duplicated in normal FedEx service because the duty cycles used by the two organizations are so different. SCE drives the vehicles on a cycle with controlled accelerations and limited top speeds, which produces a fairly high battery range. This controlled cycle is reasonable for a commuter vehicle, but FedEx vehicles are driven in a more demanding manner necessitated by the need to deliver the maximum number of packages in a minimum amount of time.) This vehicle was returned to FedEx.

At the end of July, the two G-Vans were returned to SCE for repairs. Both were reported to have problems operating in reverse gear. No problem was found. Further investigation revealed that the drivers were treating these vehicles as they would treat gasoline-powered vans, placing the gearshift in reverse without coming to a complete stop. Reverse in the G-Vans is implemented by reversing the traction motors. To avoid overloads on this motor, a safety switch prevents placing the van in reverse while still moving forward. The vans were returned to service in August, and the drivers were given further instruction on how to avoid this problem.

In September 1992, a traction motor and five battery monoblocks were replaced on one van in response to a complaint that the van stalled when turning corners or backing. The vehicle was test driven by SCE and showed a range in excess of 40 miles.

In October 1992, both electric vans were removed from service for installation of new traction motors. On one van, the original traction motor failed a diagnostic with a bad armature reading. The reason for this failure was not identified. The van was returned to service in November 1992. The motor armature isolation resistance of the other van (which had a traction motor change in September) fell short of specified values. The motor was replaced, and the van was returned to service.

Throughout November, both G-Vans experienced problems with low ranges of 20 to 25 miles on a charge. Four bad battery monoblocks were replaced on one van. The Chloride, Inc. charger's constant overcharging of the batteries (putting energy into the batteries when the battery pack was full) might have contributed to the need to replace the batteries. The van was subjected to an SCE-controlled driving test and showed a range of 40 miles. It was returned to FedEx on December 1, but complaints of low range continued. Five bad battery monoblocks, then the entire battery pack, were replaced, and all the watering blocks were also replaced. Both vans remained out of service during most of December.

In November 1992, the controller-failed signal in one van began to remain continuously illuminated while the vehicle was in operation (normally, the signal goes out a few seconds after the vehicle is started). The controller was returned for repairs. Also, auxiliary 12V power to the inside of the van failed. Upon inspection, extensive corrosion was found on the electrical connectors. These were cleaned, greased, and reassembled.

Both vans were out of service in January and February of 1993. One was returned to service in March 1993 with a new lead-acid battery pack. The second van was kept out of service for conversion to a nickel-cadmium (Ni-Cd) battery. This van resumed service in the middle of November.

In April 1993, the lead-acid battery van was out of service for three weeks (two weeks for service and one week because no trained operator was available). This van operated without problems in May 1993, but was out of service in June because its route was eliminated. In July 1993, the van was assigned to a new route in Century City.

In August 1993, the "fuel gauge" stopped functioning on the lead-acid battery powered van. The van was repaired and returned to service.

In late March 1994, the Ni-Cd battery powered van experienced a problem with the fuse in the controller. The fuse was replaced, and the van was returned to service.

The lead-acid battery powered van was removed from service on April 8, 1994. In a final performance test, this van did very poorly, indicating that the battery pack was in poor shape. The Ni-Cd battery powered van was removed from service on April 11. Its performance test went very well.

RFG. No fuel-related maintenance problems occurred with the RFG-fueled vehicles.

Gasoline Control Vehicles. In February 1994, a Dodge control van was taken to the dealer because it would not start when the engine was hot. The dealer was unable to duplicate the problem. Later testing by an independent driving service also was unable to duplicate the problem.

Statistical Summary of Maintenance Activities. Nearly 6,000 separate maintenance reports or ROs were prepared for the 109 liquid- and gaseous-fueled vehicles that participated in the two-year demonstration. This includes approximately 1,000 PM actions (oil and filter changes and chassis lubrication) and over 200 accidents or incidents that were not related to vehicle performance (e.g., repairs resulting from M-85 fuel contamination). Of the remaining 4,800 non-PM ROs that contain relevant information about the maintainability of the vehicles, slightly more than 1,900 include repairs on the engine/fuel systems (e.g., fuel injector), electrical systems (e.g., ignition control modules), and the instruments (e.g., fuel gauges). These systems, defined by specific ATA codes, are the most likely to be affected by fuel type and fuel-related technologies.

Detailed summaries of the information contained in the 1,000 PM and 4,800 non-PM maintenance reports are presented in Appendix A. Results include various measures of maintenance frequency (ROs per van, ROs per 10,000 miles, and ROs per 100 service days) and costs (labor, parts, and total) associated with all maintenance actions and, separately, for maintenance performed on selected fuel-related vehicle systems. Key results are summarized below.

Frequency of Non-PM Actions. Tables 2a and 2b contain the frequencies of non-PM actions for the various fleets involved in the demonstration, as well as statistical comparisons of the maintenance frequencies observed for the alternative fuel and control (unleaded) vehicles at each demonstration site. Fleets are defined by unique combinations of fuel type, vehicle manufacturer, and demonstration site. Table 2a compares the alternative fuel and control vans in terms of the average number of non-PM ROs per 100 service days, while Table 2b contains similar comparisons for maintenance performed on the selected vehicle systems that are more likely to involve fuel-related components.

Table 2a shows, for example, that the seven Chevrolet CNG vans averaged 441 service days per vehicle and required a total of 367 non-PM repair orders during the two-year demonstration. The rate of 11.9 repairs per 100 service days is 42 percent higher than the rate observed for the three Chevrolet unleaded vans maintained at the same demonstration site. Using a simple Poisson statistical model for the rate of occurrence of maintenance actions, it can be stated with 95 percent confidence that the frequency of maintenance on the Chevrolet CNG vans is between 17 percent and 72 percent higher than the frequency observed for the Chevrolet control vans. Because this interval does not contain the value zero, the difference in rates is said to be statistically meaningful. Maintenance frequencies were also significantly higher, based on the total number of ROs, for the Ford CNG and M-85 vans and Chevrolet propane gas vans when compared to their respective controls. There were no statistically significant differences between the maintenance frequencies of the RFG vans and those for the unleaded control vans from the same manufacturer.

By focusing on the selected (potentially fuel-related) vehicle systems (Table 2b), larger relative differences are observed in the frequency of maintenance activities among the CNG, propane gas, and M-85 vans and their respective controls. The statistically significant differences range from 46 percent higher for the Ford M-85 vans to 183 percent higher for the Ford CNG vans. In addition to the alternative fuel fleets whose total ROs were significantly higher than their controls, the Dodge CNG fleet's rate of repairs on the selected vehicle systems was significantly higher than the rate for Dodge unleaded vans. Again, there were no significant differences between the RFG and control fleets.

Non-PM Costs. Figures 3a and 3b summarize the non-PM costs for all repairs and for repairs associated with selected systems (fuels/engines, electrical, and instruments), respectively. It's important to note that there are significant differences in the reported maintenance costs for the unleaded vans among the four demonstration sites. In particular, the reported total maintenance costs on the unleaded vans at the Irvine and Rialto sites range from $250 to $750 per 100 service days, while the corresponding costs at Los Angeles and Santa Ana are less than $250 per 100 service days. These differences may be attributed to several causes including differences in vehicle duty cycles (e.g., daily mileage, type of route), price differences among vendors and local dealers, variations in vendor service response capabilities, and variations in maintenance practices among FedEx mechanics. While certain non-fuel-related warranty costs are not included in any of these figures, these "missing costs" are expected to be the same for the unleaded and

Table 2a. Relative Differences in the Number of Non-Accident Repair Orders per 100 Service Days Between Alternative Fuel Vans and Unleaded Gasoline Vans

Manufacturer	Fuel	N	Service Days per Vehicle	Total ROs [a]	RO/100 Days	Relative Difference [b]	95% Confidence Interval
Chevrolet	CNG	7	441	367	11.9	42%	(17%, 72%)
	Unleaded	3	573	144	8.4		
Dodge	CNG	7	460	383	11.9	8%	(-10%, 29%)
	Unleaded	3	544	180	11.0		
Ford	CNG	7	455	319	10.0	31%	(8%, 60%)
	Unleaded	3	630	144	7.6		
Chevrolet	RFG	7	608	295	6.9	19%	(-4%, 48%)
	Unleaded	3	660	115	5.8		
Dodge	RFG	7	605	207	4.9	-23%	(-39%, -4%)
	Unleaded	3	607	116	6.4		
Ford	RFG	7	648	241	5.3	-15%	(-31%, 6%)
	Unleaded	3	647	121	6.2		
Chevrolet	Propane Gas	7	432	465	15.4	27%	(7%, 50%)
	Unleaded	3	502	183	12.2		
Ford	Propane Gas	13	522	648	9.6	11%	(-7%, 32%)
	Unleaded	3	572	148	8.6		
Ford	M-85	20	521	649	6.2	41%	(11%, 78%)
	Unleaded	3	595	79	4.4		

[a] ROs = Repair orders.

[b] Relative difference (percent) in RO/100 days compared to unleaded vans from the same manufacturer and maintained at the same FedEx facility.

Table 2b. Relative Differences in the Number of Selected[(a)] Repair Orders per 100 Service Days Between Alternative Fuel Vans and Unleaded Gasoline Vans

Manufacturer	Fuel	N	Service Days per Vehicle	Selected ROs [(a)]	RO/100 Days	Relative Difference [(b)]	95% Confidence Interval
Chevrolet	CNG	7	441	183	5.9	183%	(98%, 305%)
	Unleaded	3	573	36	2.1		
Dodge	CNG	7	460	185	5.8	64%	(22%, 121%)
	Unleaded	3	544	57	3.5		
Ford	CNG	7	455	157	4.9	86%	(36%, 156%)
	Unleaded	3	630	50	2.7		
Chevrolet	RFG	7	608	110	2.6	16%	(-18%, 65%)
	Unleaded	3	660	44	2.2		
Dodge	RFG	7	605	75	1.8	1%	(-33%, 52%)
	Unleaded	3	607	32	1.8		
Ford	RFG	7	648	118	2.6	-6%	(-32%, 29%)
	Unleaded	3	647	54	2.8		
Chevrolet	Propane Gas	7	432	164	5.4	54%	(13%, 110%)
	Unleaded	3	502	53	3.5		
Ford	Propane Gas	13	522	254	3.7	21%	(-10%, 63%)
	Unleaded	3	572	53	3.1		
Ford	M-85	20	521	264	2.5	46%	(1%, 112%)
	Unleaded	3	595	31	1.7		

[(a)] Repair orders involving maintenance on selected vehicle systems such as instruments (ATA system code 003), Electronics (030-035), and Fuel-Engine Group (040-048).
[(b)] Relative difference (percent) in RO/100 days compared to unleaded vans from the same manufacturer and maintained at the same FedEx facility.

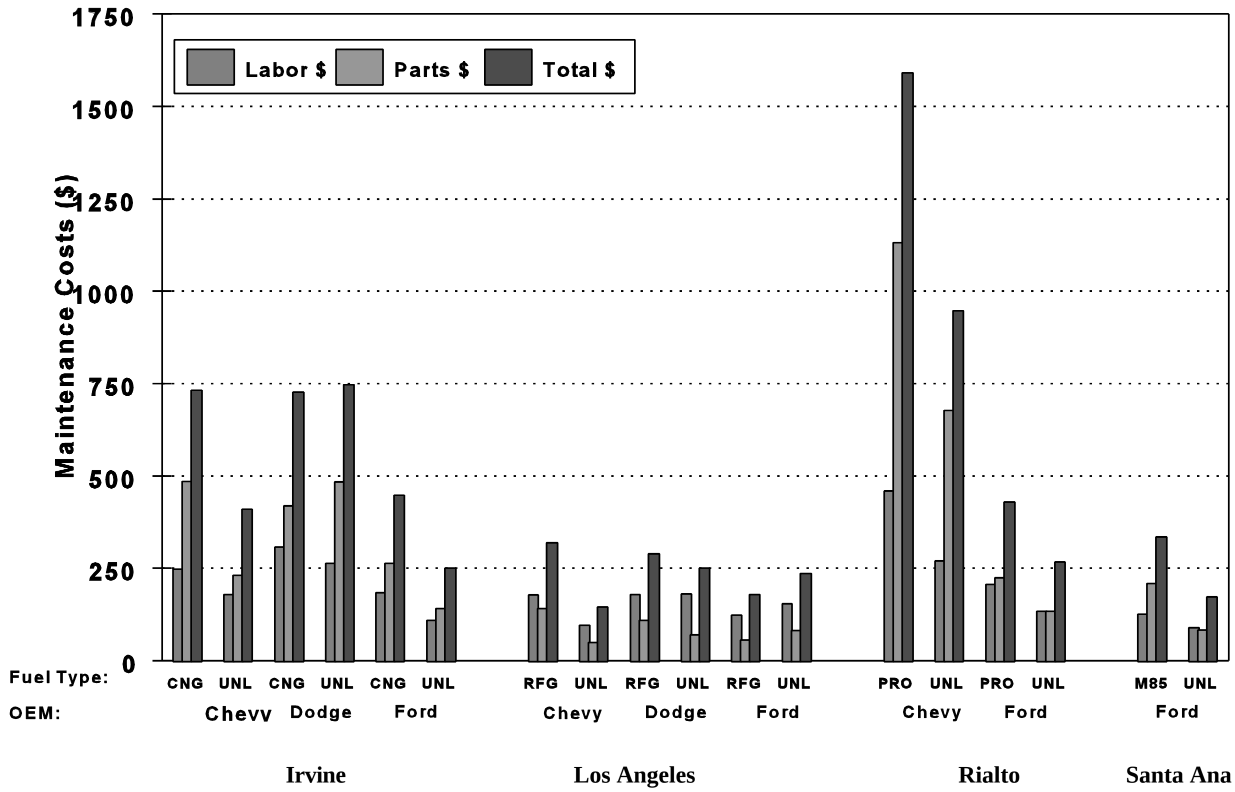

Figure 3a. Non-Preventive Maintenance Summary (All Non-Accident Repairs) Maintenance Costs per 100 Service Days by Location, OEM, and Fuel Type

alternative fuel vans. For the fuel-related warranty repairs, Chevrolet, Dodge, and the fuel system vendors (IMPCO and Suburban Propane) supplied costs to Battelle. Battelle engineers estimated the costs of the fuel-related repairs on the Ford vans. The site-to-site differences in repair costs and the missing non-fuel-related warranty costs are of little consequence as long as only vans from the same manufacturer at the same demonstration site are compared.

Figure 3a shows that, on a site-by-site basis, the total non-preventive maintenance costs for the CNG, propane gas, and M-85 vans were generally 50 to 80 percent higher than the costs for the corresponding control vans. An exception is the comparison between Dodge CNG and unleaded vans at Irvine. A similar comparison, based on the costs of maintenance on selected vehicle systems (fuels/engines, electrical, and instruments), is shown in Figure 3b. On a site-by-site basis, Figure 3b shows that maintenance costs on the potentially fuel-related systems for the CNG, propane gas, and M-85 vans are two to four times the amount for the corresponding control vans. There were no clear differences in maintenance costs between the RFG and unleaded vans.

Availability and Utilization. Nearly all of the delivery vans assigned to a FedEx station are scheduled to be in service between the hours of 7:00 AM and 8:00 PM. Mechanics generally perform maintenance when the vehicles are not in service. Because most FedEx stations usually do not keep

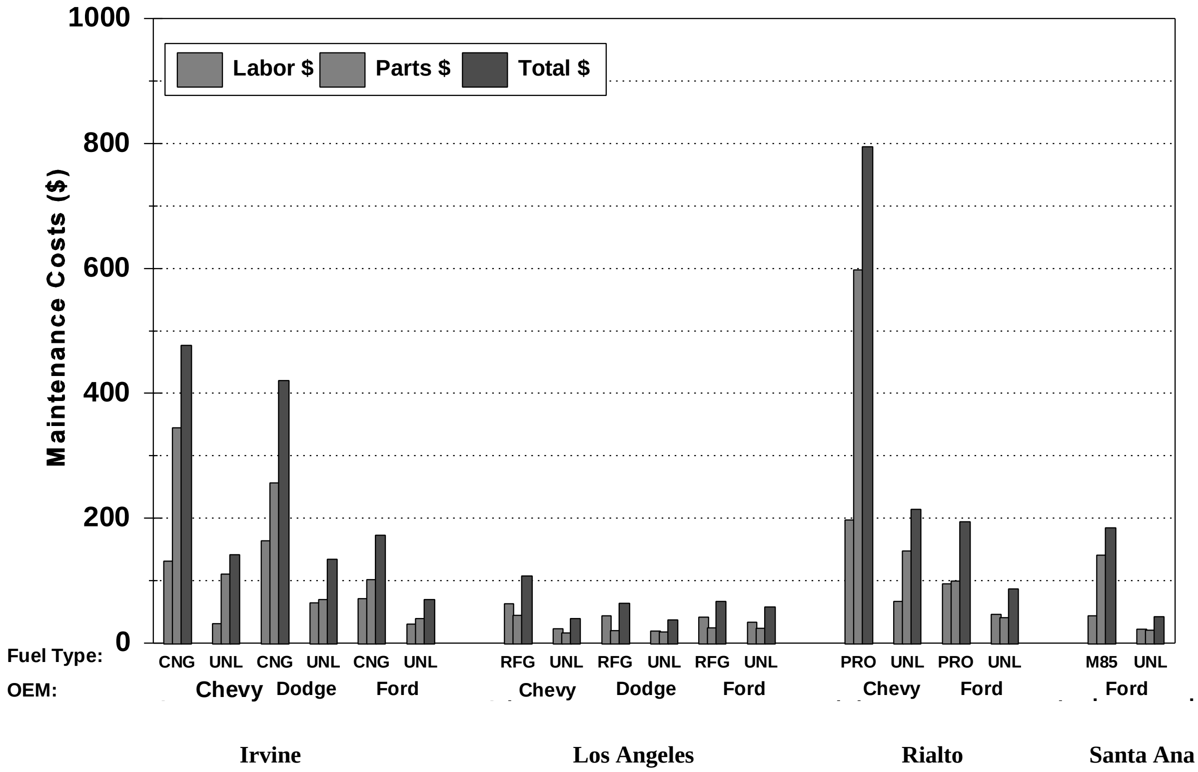

Figure 3b. Non-Preventive Maintenance Summary (Selected ATA Codes) Maintenance Costs per 100 Service Days by Location, OEM, and Fuel Type

"spare" vehicles on hand, all of the CleanFleet vans were scheduled for service five or six days per week except when they were scheduled to be in for emissions testing. (The level of delivery services performed on Saturday varies among the different stations.) Availability, as it pertains to maintenance activities, is defined as the percentage of scheduled service time that the vehicle was available for service. As discussed in the "Approach" section, vehicle availability was calculated using the reported downtime in FedEx maintenance reports and the total scheduled service time during the demonstration period. Total service time was adjusted to account for periods when the vehicles were at the ARB facility for emissions testing. Also, downtime resulting from accidents and certain maintenance "external" to vehicle operation induced maintenance (e.g., M-85 fuel contamination) is not included in the calculation of availability.

Vehicle utilization percentages are also presented. Utilization is the percent of scheduled service days that a vehicle was actually used. The averages presented below were adjusted to account for periods of time when certain vehicles were sent to the ARB for emissions testing. Thus, the results differ slightly from the results presented in the CleanFleet Quarterly Data Reports. (See, for example, Quarterly Data Report No. 8, July 1–September 30, 1994.) Utilization is always less than or equal to availability. The difference between these values represents the percent of scheduled service time that a vehicle is available but not utilized.

VEHICLE MAINTENANCE

Table 3 contains estimates of vehicle availability and vehicle utilization for each fleet of vans. Average availability varied from 88 percent for the Chevrolet propane gas fleet at Rialto to 98 to 99 percent for several fleets of unleaded and RFG vans. The average availability of vans from each alternative fuel fleet was between 4 percent lower and 2 percent higher than the average availability of the unleaded vans at the same location. No consistent pattern was detected.

Utilization varied from 83 percent for the Chevrolet CNG fleet to 97 percent for the Ford unleaded fleets at Irvine and Los Angeles. Generally, utilization was 1 percent to 7 percent lower than availability. Exceptions included the Dodge CNG fleet (9 percent lower) and the Chevrolet CNG fleet (11 percent lower). Under normal fleet operations, one would expect to see a consistent difference between availability and utilization, especially in a package delivery service such as FedEx, which must have a minimum number of vehicles available *at all times*. Comparing the utilization of alternative fuel fleets with that of the corresponding control fleets, the average utilization of RFG, propane gas, and M-85 vans was within 5 percent of the average utilization for the unleaded vans. On the other hand, the utilization of the Chevrolet and Ford CNG vans was 7 to 9 percent lower compared to the corresponding unleaded vans at the same locations. Two possible reasons for these differences are (1) the Irvine station may have had a greater need for vans that could be assigned to longer routes (over 100 miles per day), and (2) there may have been times when "driveability" concerns caused the couriers to choose available unleaded vans even though the CNG vans were not officially out of service for maintenance. Other factors that can affect utilization include the availability of spare vehicles, changes in delivery schedules, employee preferences for certain types of vehicles, and variations in maintenance scheduling practices.

Table 3. Vehicle Availability and Utilization

Location	Fuel	Manufacturer	Average Availability [a]	Average Utilization [b]
Irvine	CNG	Chevrolet	94	83
		Dodge	93	84
		Ford	94	88
	Unleaded	Chevrolet	95	90
		Dodge	91	87
		Ford	98	97
Los Angeles	RFG	Chevrolet	98	95
		Dodge	98	91
		Ford	98	94
	Unleaded	Chevrolet	99	92
		Dodge	99	96
		Ford	98	97
Rialto	Propane gas	Chevrolet	88	86
		Ford	96	93
	Unleaded	Chevrolet	91	89
		Ford	96	92
Santa Ana	M-85	Ford	97	94
	Unleaded	Ford	99	95

[a] Availability is defined as 100 (T-D)/T, where T is the scheduled service time and D is the downtime required for maintenance.
[b] Utilization is defined as 100 U/T, where T is the number of scheduled service days and U is the number of days that the vehicle was actually used by FedEx.